The development of executive function

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Executive Function Development:

Towards More Optimal Control Coordination with Age

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Abstract

Emerging executive function, which allows children to control their thoughts and actions, is a major predictor of life success. A key challenge for children is to engage control in a way that matches ever-changing task demands. In addition to engagement of *more* control resources and more mature control strategies, executive function development also reflects more *flexible* coordination of available control strategies with age. More optimal control coordination (or meta-control) ensures dynamic adjustment of control engagement to better match moment-to-moment variations in task demands and results in more economic cognitive functioning.

Keywords: executive function; cognitive control; cognitive development; meta-control; children.

Executive function development:

Towards more optimal control coordination with age

Whether playing video games, following instructions from parents, or working on homework, children often need to engage executive function to control their thoughts and actions and to reach their goals (e.g., win the games, get the chore or assignment done). Emerging executive function is indeed among the best predictors of academic achievement and later life success (1,2). Effortful activities (tasks) and the context in which they are accomplished change constantly, which requires children to flexibly adjust control engagement to match these moment-to-moment variations in task demands (e.g., engage more effort to focus on homework if the TV is on).

In this article, I argue that executive function development is not limited to engagement of *more* control, due to a quantitative increase in cognitive resources (e.g., growing working memory capacity) and related metabolic activity/structural changes in the prefrontal cortex, but is also driven by *better* control engagement with age. Specifically, executive function is not limited to the growing efficiency of the same processes and strategies used throughout childhood. It is also driven by qualitative changes, resulting (1) from the emergence of new control strategies, that is, new ways to implement and/or combine executive processes (e.g., using verbal labeling, engaging control proactively), and critically (2) from more flexible and optimal coordination of this expanding repertoire of control strategies. In other words, children more ably tailor control engagement to the specific demands of each task/situation with age.

The present review focuses primarily on coordination of control strategies. After reviewing evidence suggesting that increasingly flexible control engagement results from an expanding repertoire of control strategies as well as better coordination of this repertoire in early and middle childhood, I will address how these changes yield more economic cognitive functioning and the potential mechanisms that underpin control coordination. Although this article focuses on early and middle childhood (where most findings are available), the principles discussed here potentially apply earlier and later in development.

An expanding control repertoire for more flexible control engagement

Cognitive control is necessary in situations where goals cannot be attained through routines (e.g., going to school for the first time), distractions must be ignored (e.g., noisy environments), irrelevant actions must be suppressed (e.g., petting a stray dog), or goal-relevant actions are difficult to select (e.g., pressing the right key sequence for a novice piano player). Although all of these situations require mental effort, how much effort and how control must be engaged depend on the specific demands in a given situation, that is, the nature of goal-relevant and irrelevant information and of the mental operations that must be carried out to reach that goal (i.e., accomplish the task).

As children grow older, they engage control in a more flexible and differentiated fashion depending on task demands. Supporting evidence comes from studies that examined the “structure” of executive function, that is, the extent to which cognitive control is underpinned by the same or different processes across situations and task demands. Most of these studies used confirmatory factor analysis, a statistical method that summarizes performance on multiple tasks by one or more theory-driven latent factors. In adults, three partially separable dimensions of executive function have been reported: *inhibition* of goal-irrelevant actions, *shifting* between multiple tasks or mental operations, and information maintenance and updating in *working memory* (3), but see (4), for a revised model including a common executive dimension along with shifting- and updating-specific dimensions). The three dimensions reported in adults seem to differentiate progressively during childhood. Most studies report only one dimension in young children, two dimensions (albeit different ones across studies) during elementary school, and three dimensions in later childhood and adolescence (see (5), for a synthesis). With age, children either progressively rely on increasingly specialized control processes or, perhaps more plausibly, progressively combine these processes differently depending on task demands, hence showing increasing differentiation of control engagement across situations.

Growing flexibility of control engagement is perhaps most conspicuous when new control strategies emerge. Verbal strategies (e.g., describing pieces out loud while solving a puzzle), for instance, are especially efficient to guide behaviors (e.g., (6)) and increase during childhood (7). In the task-switching paradigm, which requires switching back and forth between two tasks (e.g., color- and shape-matching), preventing verbal strategies, such as saying “color” or “shape”, through articulatory suppression (e.g., repeating the days of the week) impairs adults’ cognitive control performance to a greater extent than non-verbal dual tasks (e.g., (8)). Articulatory suppression has the same detrimental effect at 9 but not 6 years of age, suggesting that younger children do not use verbal strategies yet when switching between tasks (9).

Similarly, proactive control strategies become more frequent with age (10). Proactive control consists in anticipating and preparing in advance for foreseeable task demands, to minimize the effects of interfering information when finally doing the task (e.g., gathering thoughts before a class presentation). By contrast, reactive control is engaged in the moment to resolve interference when it arises (e.g., improvising during the presentation) (11). Young children rely exclusively on reactive control, whereas children 6 years and older engage proactive control in a variety of tasks: tapping response inhibition (12–14), set-shifting (15), working memory (16), or prospective memory (17).

This age-related shift from reactive to proactive control is observed, for instance, in the AX-Continuous Performance Test (AX-CPT), which requires responding to specific prime-probe combinations (e.g., when a dog is followed by a cat). In this task, preschoolers engaged most mental effort (as evidenced by pupil dilation change) relatively late by reactively retrieving prime information after probe onset (did I see a dog before the cat?). In contrast, older children engaged mental effort earlier, right after the prime, by maintaining the prime in working memory and anticipating the onset of its associated probe (there is a dog now, a cat will probably follow) (12). Consistent results have been found in a working memory span task where children had to reproduce sequences of animals that they just heard. After hearing the animal names, preschoolers immediately recalled the first item and then reactively retrieved each subsequent item, whereas elementary school children proactively planned the entire response sequence before starting to respond (16). Importantly, proactive control does not merely replace reactive control after 6 years of age, but adds to it. Adults flexibly engage either form of control as a function of task demands (18).

Better control coordination

Increasingly flexible executive function engagement with age reflects the expanding repertoire of control strategies that children can draw from. However, repertoire growth may not be the only contributing factor. Coordination of the control repertoire – or meta-control – may become more optimal with age. Control coordination is critical because each control strategy is associated with specific advantages and disadvantages that make it more appropriate for some task demands than others. Therefore, optimal performance likely results from selection of the most appropriate strategy (e.g., the least demanding strategy when fatigued).

Reactive and proactive control strategies illustrate the benefits of having complementary strategies available in the control repertoire. Proactive control is generally more efficient than reactive control but at the cost of more mental effort, due to maintenance of task-relevant information and related prefrontal cortex activity over sustained periods, whereas reactive control relies on short information activation and transient prefrontal cortex activity (18). However, proactive control is efficient only if upcoming task demands can be reliably predicted. When they cannot, one must be able to engage reactive control instead to resolve interference, even though this control mode is less advantageous overall. Proactively preparing for a task that cannot be reliably predicted may even be a waste of mental effort. Reactive control is also more adaptive than proactive control when preparation itself requires more mental effort than simply engaging control reactively. Consistently, compared with children who engage reactive control, 6-year-olds who engage proactive control performed better in a delayed match-to-sample task (where they saw a target and after a delay had to press the corresponding picture) when actively maintaining target information during the delay was easy, but worse when distraction during the delay made proactive control more challenging (14).

At age 5, children primarily engage reactive control, not because proactive control is not yet part of their control repertoire, but because of suboptimal coordination of these control strategies (15). Specifically, in the cued task-switching paradigm, which necessitated switching between sorting a target by color and shape, 10-year-old children proactively prepared for the next target each time the upcoming task was reliably signaled ahead of time by a visual task cue (e.g., by covertly saying the relevant task name, “color” or “shape”). Such proactive preparation is especially efficient because knowing which task is relevant helps to process the relevant dimension of the next target faster (see (19)). However, 5-year-olds stuck to reactive control, even when proactive control would have been potentially more efficient. They engaged proactive control only when the task cue disappeared on target onset, making it more difficult to reactively retrieve the relevant task. Therefore, 5-year-old children may fail to realize when proactive preparation is more advantageous or have a higher threshold to engage this more-demanding strategy, but they can engage it with external guidance. Coordination of reactive and proactive control strategies may be sub-optimal initially and fine-tuned with age. Indeed, coordination of reactive and proactive control becomes increasingly flexible through early adulthood (20). Further research is needed to determine whether this is also true earlier in development when proactive control may not be available at all.

Some 5-year-olds also showed evidence of control coordination in a version of the task-switching paradigm in which children were instructed to alternate on every second trial without any external task cues (21). The most obvious strategy consisted in keeping track of the current position in the task sequence (e.g., color, color, shape, shape), which is demanding on working memory. Children with the highest working memory capacity applied this strategy successfully, ensuring high accuracy, whereas those with the lowest working memory capacity either never switched or switched randomly, leading to low accuracy. Most interestingly, some children with medium working memory capacity started applying the obvious strategy but with little success, as shown by a quick drop in accuracy across trials, because this strategy was too demanding for their working memory capacity. Then these children switched to less demanding and thus more adequate strategy (probably basing response on task name rhythmicity) that ensured both accurate and fast responses. Therefore, at least some 5-year-olds can coordinate control strategies well enough to switch to a more appropriate strategy after initial failure.

More economic cognitive functioning

Increasingly optimal control engagement with age does not necessarily mean engaging *more* control or more often; it actually often entails *less* control. Task demands change frequently and optimal executive function entails matching control engagement with these variations, increasing control when demands increase but also releasing it when demands decrease, to preserve cognitive resources or perhaps engage them in another task. Constant control engagement may be neither viable, due to constantly high mental effort and glucose consumption, nor even desirable. For example, high control engagement may lead individuals to ignore goal-irrelevant but potentially important information in the environment (22), or result in suboptimal social interactions (e.g., behavioral inhibition (23)). Indeed, bottom-up, data-driven processes may even be more appropriate for some activities (e.g., creative thinking; (24)), and although control is especially efficient when learning a new skill, less control is more beneficial when the skill has been mastered (25).

With advancing age, more economic functioning is promoted by more flexibly adjusting control engagement to variations in task-demand. In cued task-switching paradigms where the relevant task rarely changes, 5-year-olds actively determine the relevant task on all trials by semantically processing each task cue. This "semantic-processing" strategy necessitates control to identify the relevant task on every trial, whether or not that task happens to repeat or change (26,27). By contrast, 10-year-olds and adults expect by default a task repetition (which actually happens on most trials). They carry on the same task across trials, unless they detect a perceptual change in task cues, which is indicative of a task switch. This “perceptual-change” strategy allows flexible engagement of control only on rare trials where the task actually changes and disengagement of control on all other trials, resulting in more economic cognitive functioning (26).

Furthermore, in the Go/No-Go task, which requires inhibiting responses to rare No-Go targets, control-related event-related potentials (i.e., electrophysiological brain activity related to cognitive functioning recorded over the scalp) are much more pronounced in magnitude when the response is inhibited than when a response is given in adults, suggesting that adults engage more control when the response must actually be suppressed. In young children, they are almost just as pronounced on both types of trials (28,29), suggesting that children more rigidly engage substantial control on both types of trials. Similarly, 8 to 12-year-old children strongly recruit supplementary motor areas (SMA) and pre-SMA for both task changes and task repetitions in the task-switching paradigm, whereas adults recruit these regions to a greater extent when the task changes, that is, on the most demanding trials (30). Consistently, a recent review of brain activity associated with cognitive control showed that with age children’s performance is increasingly supported by posterior regions specialized for specific aspects of the tasks, hence showing progressive disengagement of the prefrontal cortex and control resources (31). By analogy, as one practices the piano, playing music progressively requires less control.

How is control coordination achieved?

Adequacy between task demands and available control resources is critical to control coordination. According to the Expected Value of Control (EVC) model of adulthood cognitive control (32), the costs (i.e., mental effort) and benefits (i.e., rewards) of concurrent tasks are weighed to decide which task is most advantageous and how much control should be mobilized to accomplish it. Specifically, the dorsal anterior cingulate cortex may integrate information on task demands and internal states (from higher-order perception regions and orbitofrontal cortex, respectively) to modulate control in other brain regions (lateral prefrontal cortex, basal ganglia). Although the model focuses on decisions on *how much* control must be engaged, the benefits/costs weighing process could be expanded to decisions about *how* to best engage control, and thus account for coordination of control strategies. Indeed, research on strategic development suggests that cognitive strategy selection does depend on automatic calculation of benefits/costs ratios of available strategies (e.g., (33).

As task demands influence which strategy is most appropriate, detection and evaluation of task demands are critical to the calculation of costs and benefits of control strategies. Adults efficiently detect variations in tasks demands across situations and use them to avoid unnecessary mental effort. For instance, in the Demand Selection Task (DST), where they are given the choice between two versions of a task (e.g., the task-switching paradigm) that differ in task difficulty, adults more often decide to complete the easier version (e.g., the one with the smallest number of task switches) (34). Children seem to detect task-demand variations before they use them to modulate control engagement. For instance, 6 and 7-year-olds, but not 5-year-olds, spend more time studying items that are harder to learn than items that are easier to learn, even though 5-years-olds can already identify difficult and easy items (35).

Just as important as task-demand evaluation is the evaluation of internal states and cognitive resources (36). Given the exact same task demands, the best way to engage control varies as a function of individual traits (e.g., working memory capacity) and states (e.g., motivation, fatigue, emotions). For instance, strategies highly demanding on working memory are most adaptive for individuals with higher working memory capacity when they are not fatigued. Consistently, in the task-switching paradigm, children and adults with higher working memory capacity are most likely to engage strategies with high working memory demands (e.g., proactive preparation) (18,21). Similarly, children with lower processing speed are less likely to use verbal strategies spontaneously and thus benefit more from incentives to do so (37).

Finally, control coordination necessitates information about performance success both to evaluate the efficiency (i.e., benefit and cost) of a particular control strategy for specific task demands, and to predict future chances of success (36). Children need to get this information by monitoring their performance. Important aspects of performance monitoring, such as error detection and feedback processing, improve with age (e.g., (38,39)), potentially contributing to more optimal control coordination. For instance, children increasingly use past experiences to infer greater amount of information from the feedback they receive (e.g., not only when to switch task and which task to switch to, but also how long the task will likely remain relevant; (40)).

To date, little is known about how these processes change during childhood to support increasingly flexible control engagement. For instance, with practice and experience, children may accumulate knowledge on the costs and benefits of each strategy, facilitating flexible coordination of these strategies (see (33)). A related question is to what extent control coordination is intentional and control strategies consciously represented. Strategy representations may become more conscious as they refine (i.e., integrate further cost/benefit information) with age and, as a consequence, become easier to coordinate (see (41)). Consistently, recent evidence suggests that children better monitor proactive control engagement with age. Specifically, in a cued task-switching paradigm where the task cue was presented early (allowing children to proactively prepare for the next target) and subsequent target onset was self-paced, 10-year-olds more systematically decided to strategically trigger the target after finishing task preparation (as evidenced by gaze trajectories), whereas 6-year-olds often triggered the next target while task preparation was not completed yet (42).

Conclusion

In brief, there is more to executive function development than a mere quantitative increase in the efficiency of executive processes. Development is also driven by changes in the control strategies available to children, which comes with the challenge of coordinating adaptively this expanding control repertoire. With age, children better adjust control engagement (i.e., amount of control and strategy selection) as a function of moment-to-moment variations in task demands. Increasingly optimal control coordination results in both more efficient and more economic cognitive functioning. In other words, executive function development reflects, in part, better use of existing control resources with age.

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